Tribology Research
at
Argonne National Laboratory

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Workshop: Materials Research and Manufacturing for Alaska

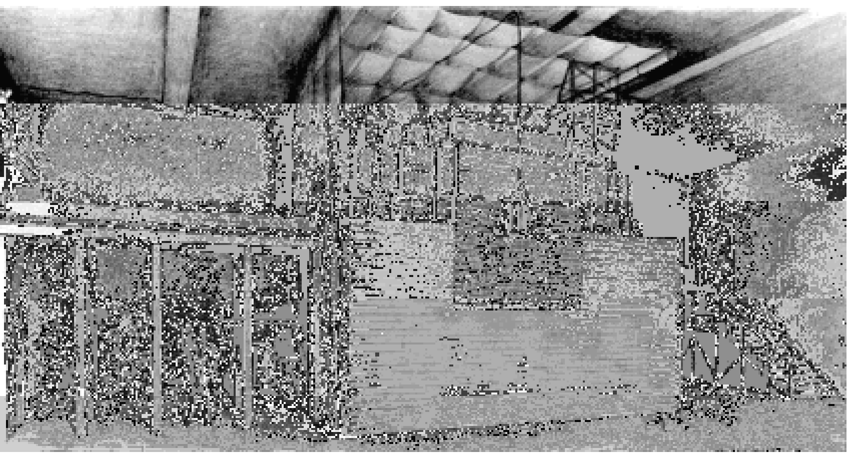
February 9th & 10th, 2001

University of Alaska - Fairbanks

Outline

- History of Argonne & Tribology Research
- Staff
- Facilities
- Near Frictionless Carbon
  - NFC Coating Technology
  - NFC Coating Tribology

Argonne History



CP-1 - world's first self-sustaining nuclear chain reaction

- **Argonne history dates back to the la 1930's with Enrico Fermi's efforts to demonstrate nuclear chain reaction - Univ. of Chicago Stagg Field Squash Courts.**
- **Argonne National Laboratory established (1946) - nation's first 'national' laboratory**
- **Until early 70's Argonne's research focused on development of *nuclear reactor technology* for power production, and, *basic research***
- **Mid-70's (oil embargo) - DOE forme and role of national labs expanded to include *all forms of energy productio and use***

Argonne
Operated by the U of Chicago for DOE

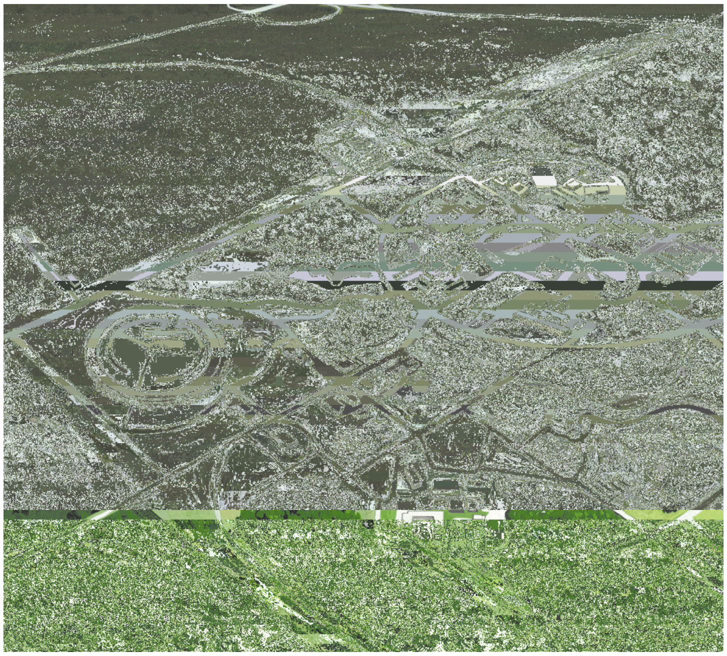
4200 employees

- 1775 scientists & engineers
- 800 hold Ph.D.s

$470 M budget

Two sites

- Argonne - East (1700 acres SW of Chicago) - 3700 employees
- Argonne - West (900 acres - INEEL) - 500 employees



- Major Programs in:
  - Energy and Environmental Science & Technology
  - Nuclear Technology
  - Basic Sciences
  - Advanced Photon Source

Tribology R & D History

Tribology effort initiated at ANL (1983)

- Lead lab for DOE national Tribology Program (surface engineering, lubricants, and materials)

Tribology Section Formed (1987)

Major R&D Efforts

- Nitride & Carbide Coatings
- High Temperature Lubricious Coatings
- Gas Turbine Coatings
- Metalforming Lubricants
- ***Near Frictionless Carbon (NFC) Coatings***
- ***Boundary Layer Lubrication***

Tribology Research

Programmatic Funding - not Block Funding

Major DOE Programs - Transportation (DOE funded)

- CIDI and SIDI Engine Components (e.g. Fuel Systems)
- Compressors/Expanders - Fuel Cells
- Boundary Lubrication - APS

Coating Development

- ***Near Frictionless Carbon***
- Boric-Acid Solid Lubricants
- High Temperature Metallic Coatings
- C/C Composite

Friction and Wear Testing

- Dry Air and Inert Environments
- Fuels
- Engine Lubricants
- Vacuum

Tribology Section
Strengths/Focus

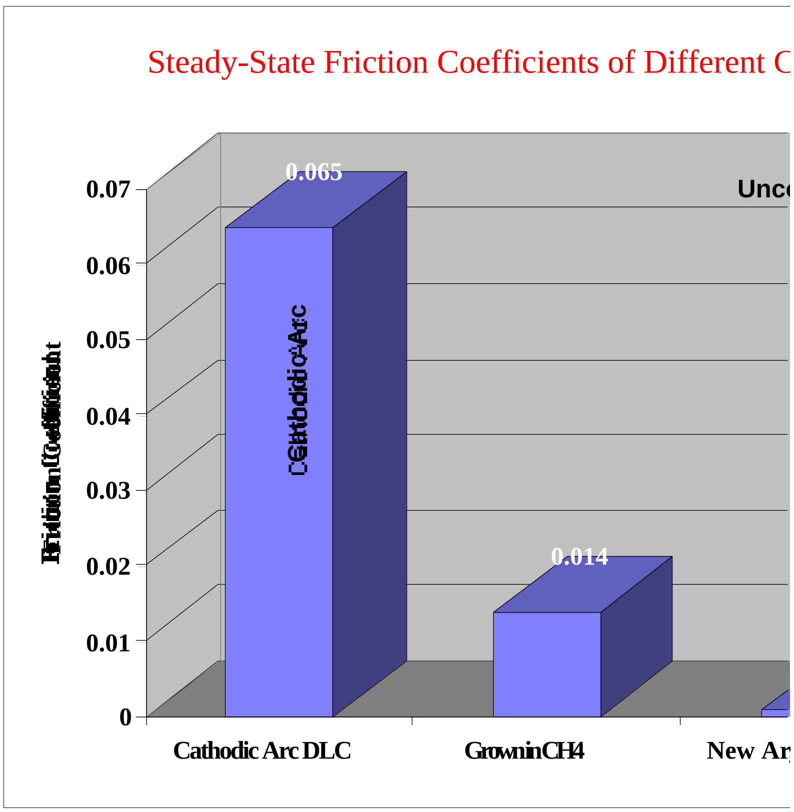
Engineered Surfaces - Coating Development

Material/Surface Characterization

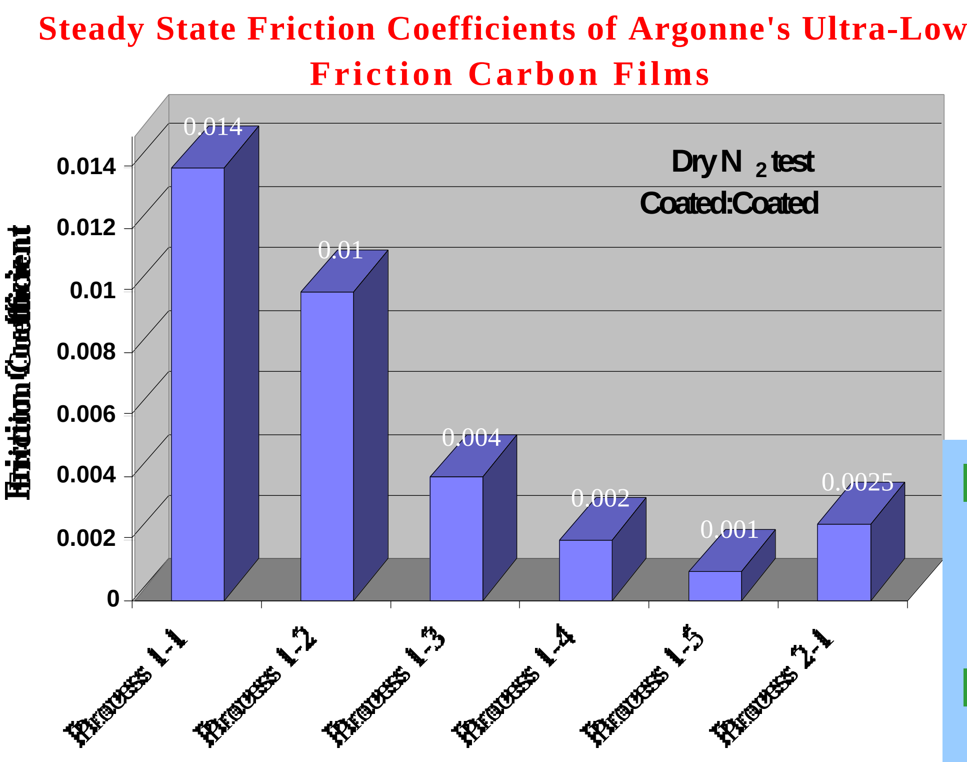
Lab Scale Friction & Wear Measurements

What Argonne Has Developed

A new process or procedure resulting in the formation of a very hard and near-frictionless carbon film (steel-on-steel: 1.1, steel-on-Teflon: 0.04)



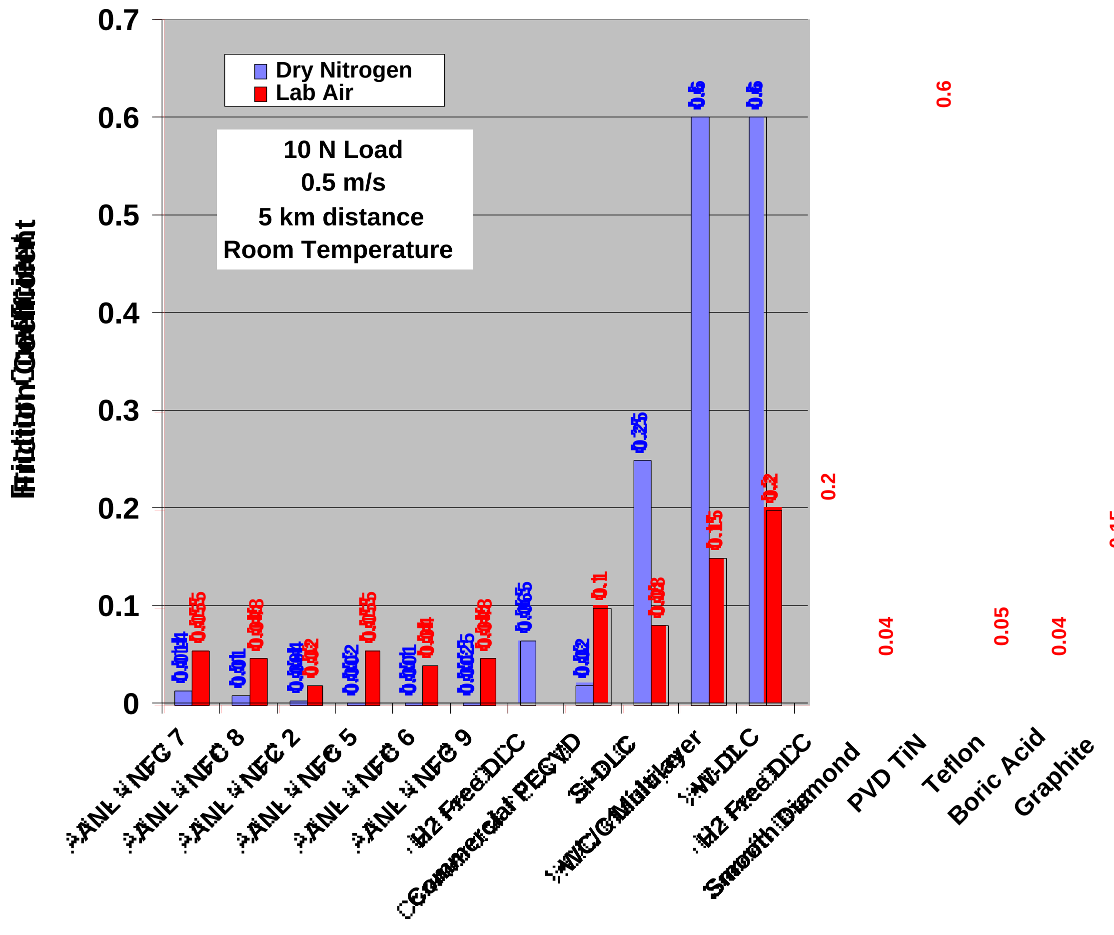
Why All the Interest in NFC?



- Extremely low friction coefficient under dry sliding conditions
- Ultralow friction obtainable by proper selection of process conditions

Comparison of NFC Coating Performance with Commercial DLC Coatings

- Pin-on-Disc Test Configuration
- Dry Sliding Environment
- Proper control of deposition process results in significant improvements in frictional performance



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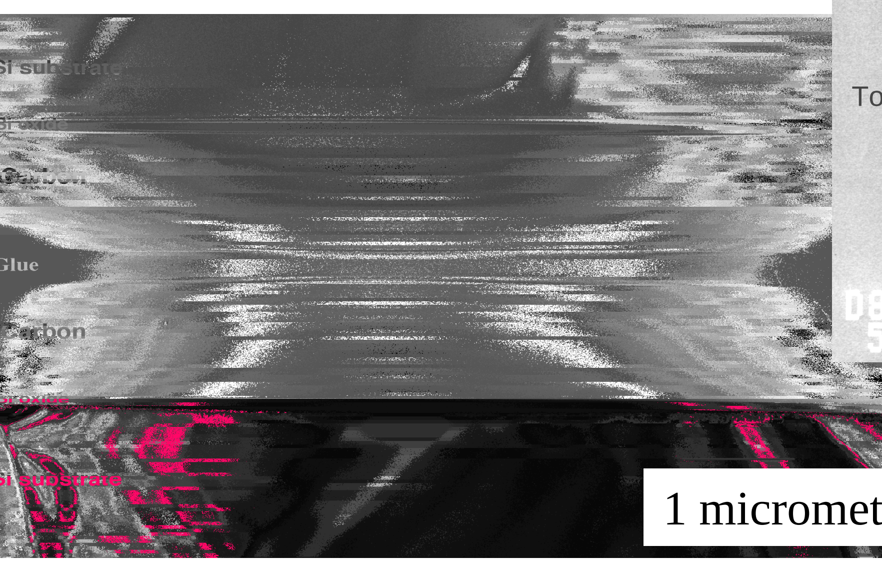
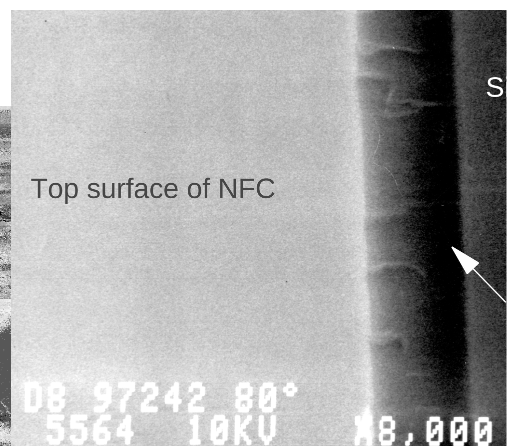
Tribology Section

Near Frictionless Carbon - NFC

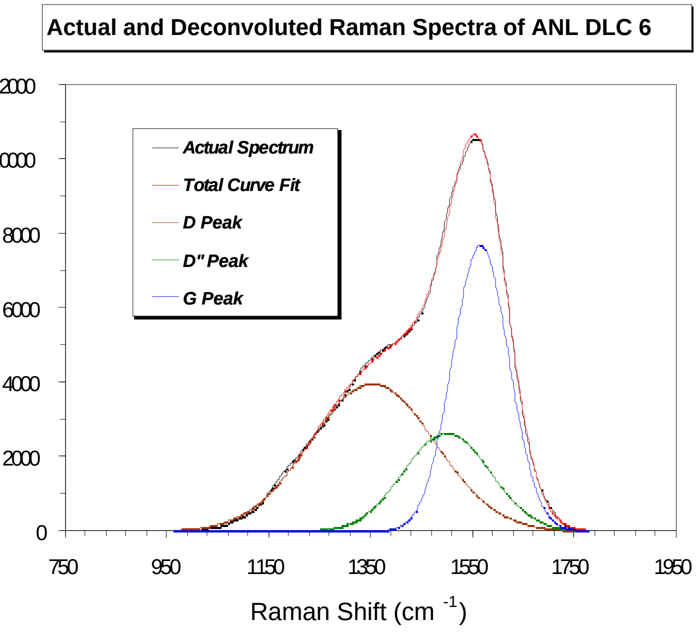
- Amorphous form of carbon exhibiting properties comparable to diamond
- Can contain large quantities of hydrogen which significantly affects the properties of the film
- Can also contain small amounts of other elements

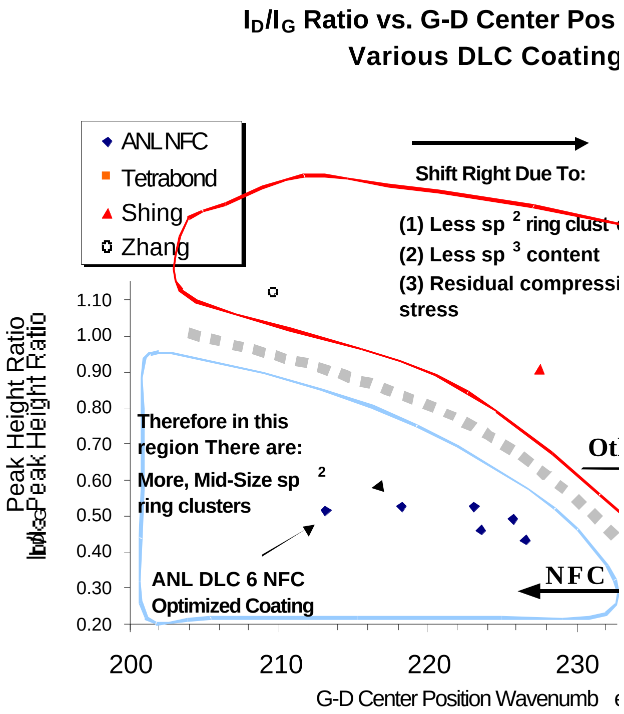




Raman Analysis of Unique Chemical Nature of NFC Coatings

NL process produces films which are
otally unique - unique combination of a
rge number of sp2 disorder rings in the
mall to mid size range. The friction
oefficient is strongly correlated to the
-D parameter





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Coating Hardness

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oating is NOT
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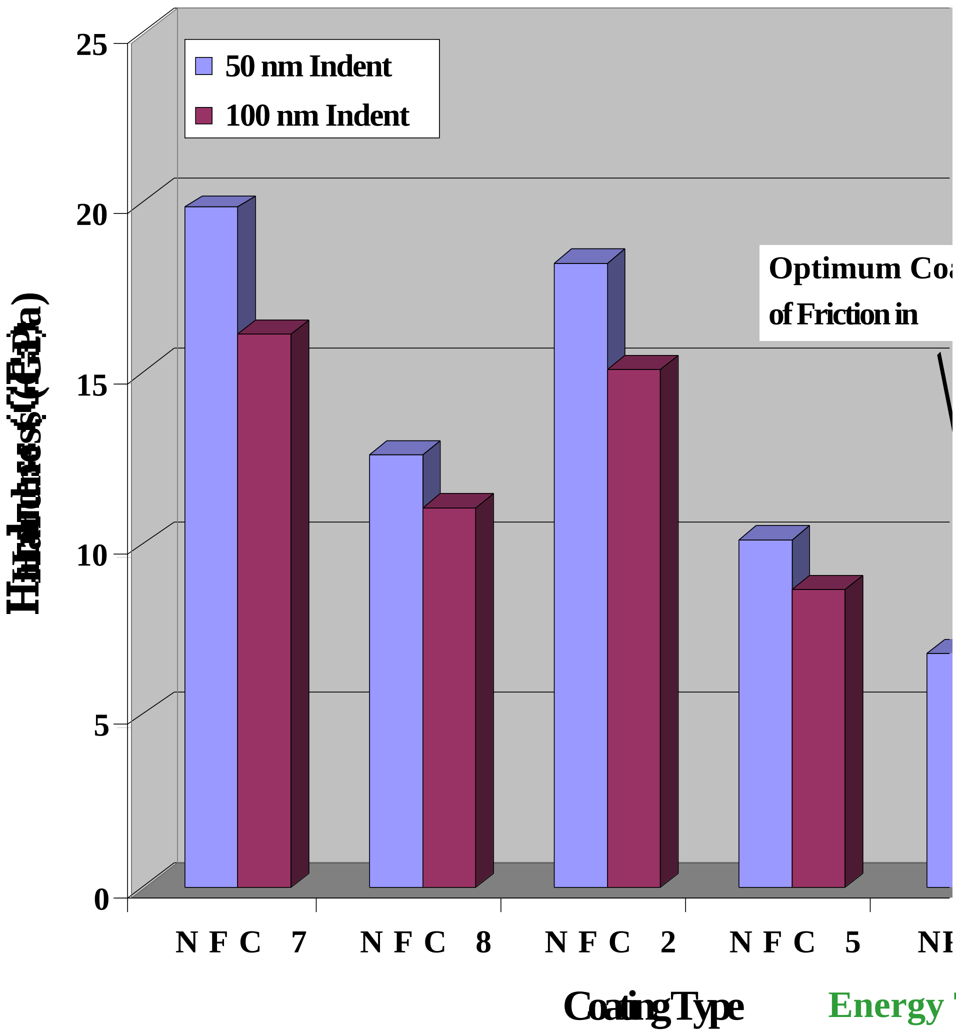
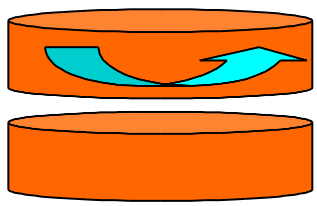
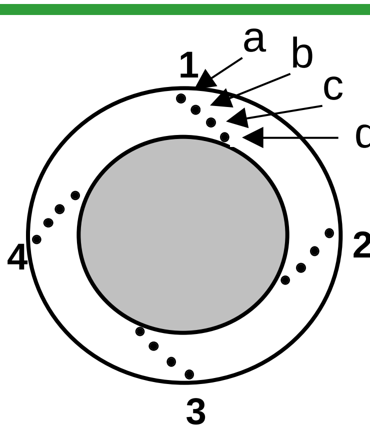
oating

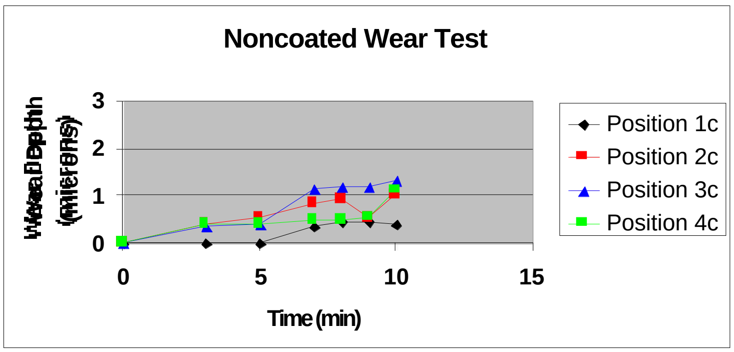


Wear of NFC-Coated Thrust Washers

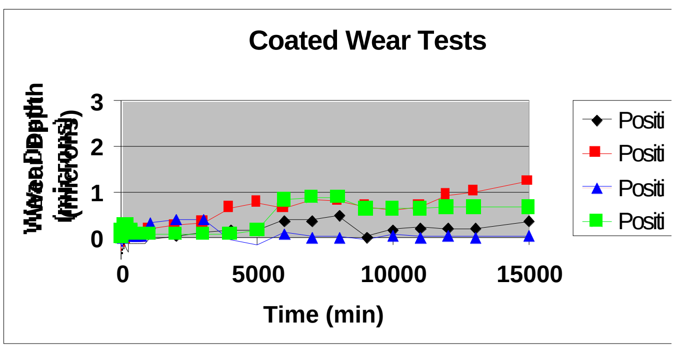




Development of coatings for novel gas bearing design for a fuel-cell turbo-compressor/expander



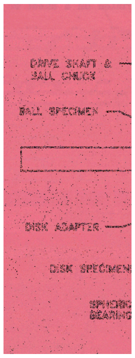
NFC-coated thrust washer has exceeded 15,000 min. of testing with no indication of wear (5/15/99)

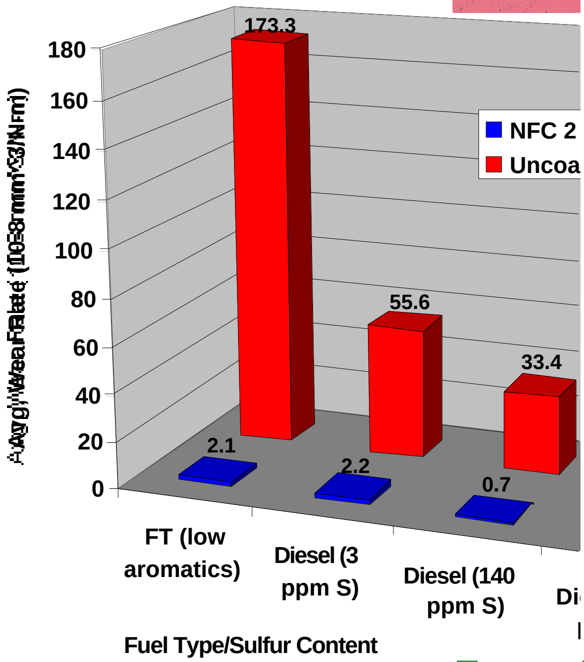


Impact of Sulfur on Durability

- Benchtop lab tests (HFRR and BOTD) demonstrate role of sulfur-bearing compounds on wear of steels - higher wear associated with lower sulfur content
- Tests with DECSE fuels in progress
- Application of NFC coatings significantly improves wear performance
- Testing of NFC coatings applied to fuel injection components in progress

BOTD - ball on three disc

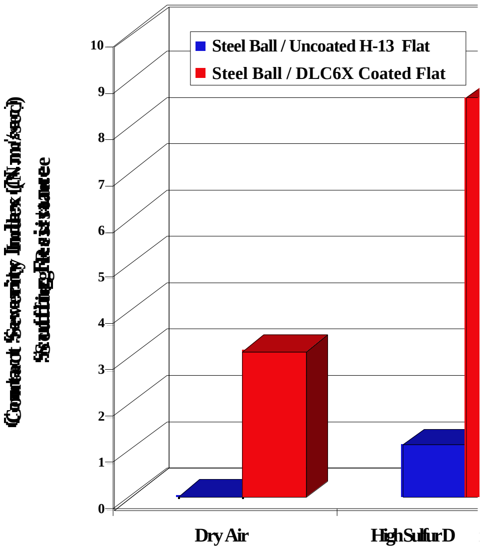




Impact of Sulfur on Reliability/Scuffing Behavior

- Conducted with the HFRR
  - Sliding speed progressively increased until scuffing
  - Scuff resistance compared by the parameter μPV - designated contact severity index
  - Test with regular diesel fuel (500 ppm S, 23% aromatics) and F-T synthetic fuel (no Sulfur, no aromatics)
- NFC coating increased the scuff resistance of steel surfaces by more than 10 times
  - No scuffing until NFC coating worn through

HFRR - high frequency reciprocating rig



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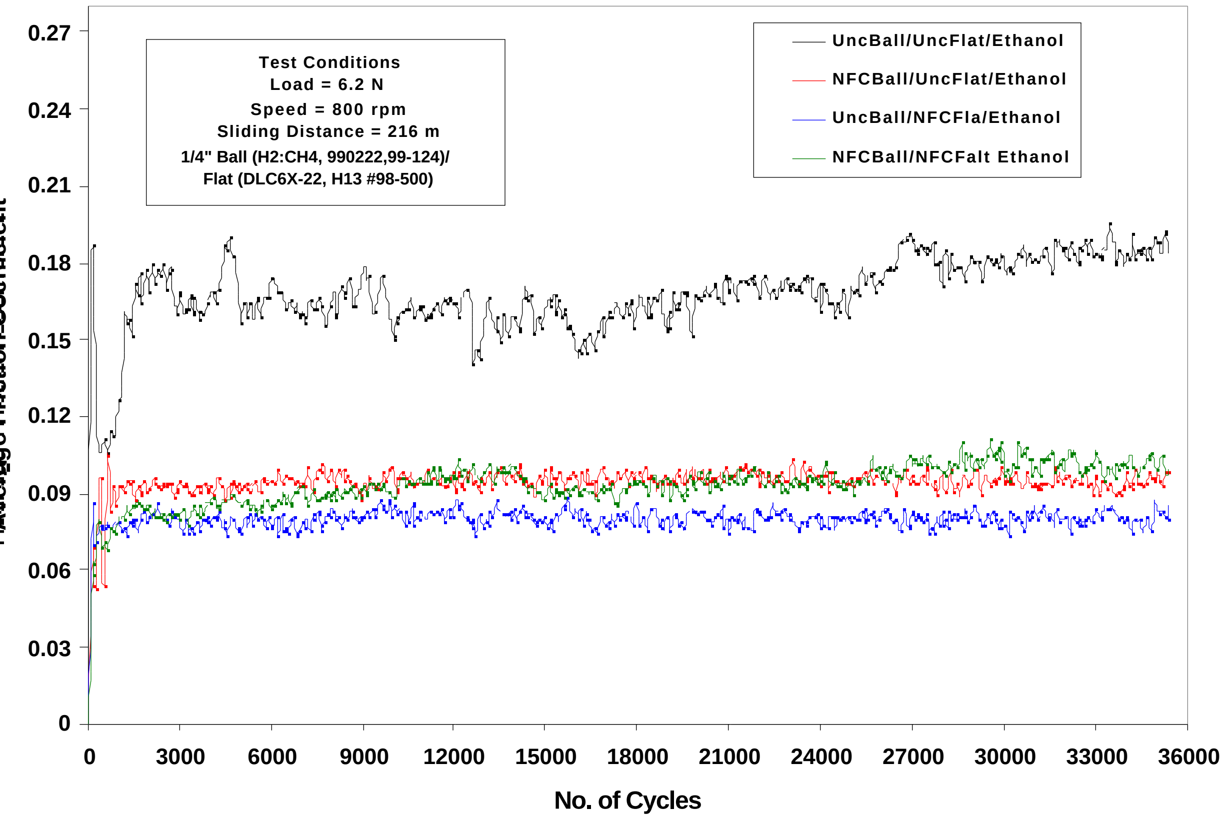
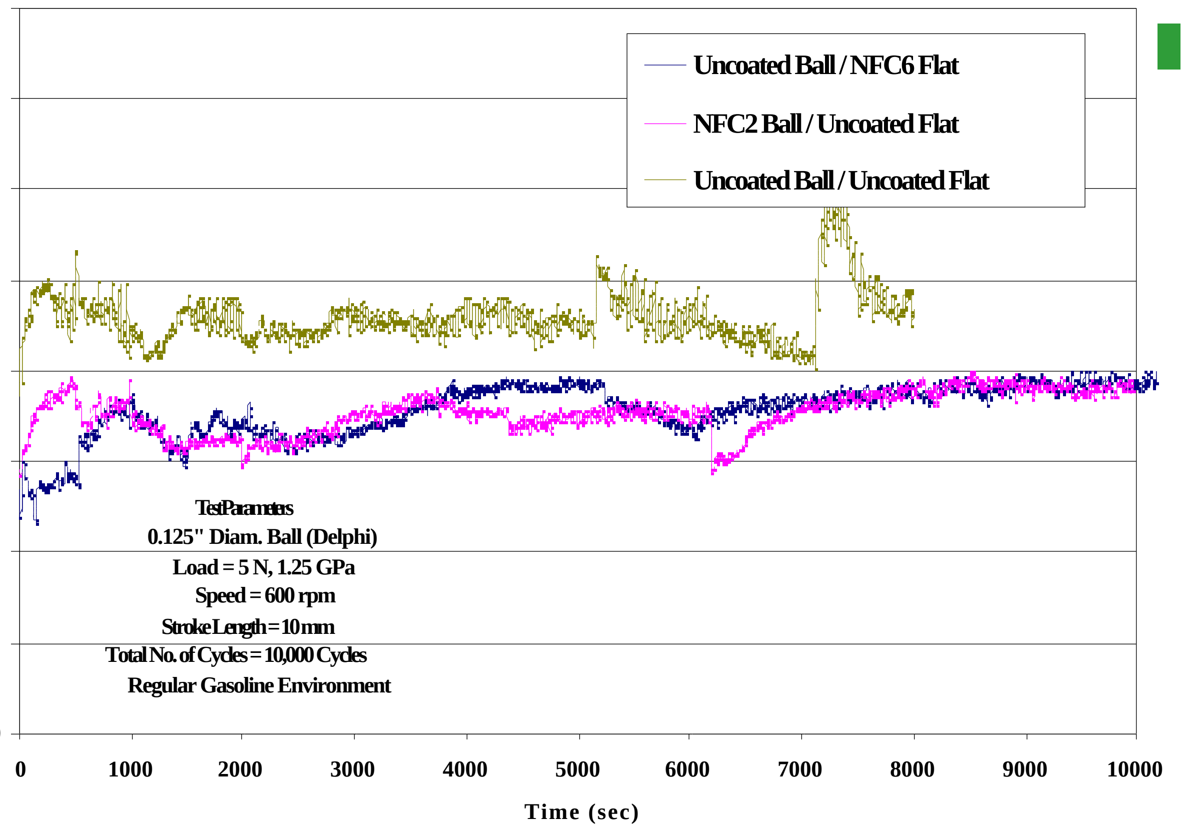
Impact of Coating on the Friction Coefficient in Ethanol



Significant Reduction in Friction Coefficient with NFC Coatings

Impact of NFC Coatings on the Frictional Behavior in Conventional Gasoline



- NFC coating reduced the friction coefficient by 1 to 20 %

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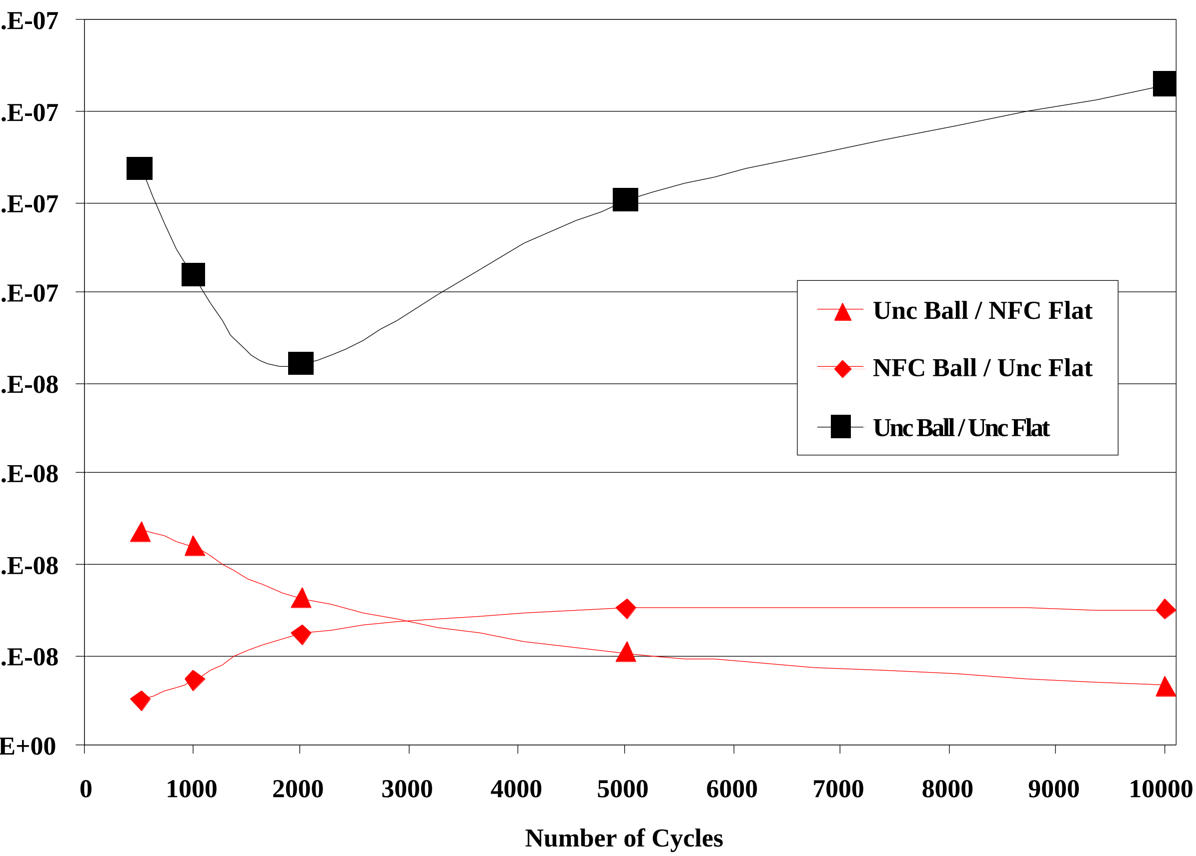
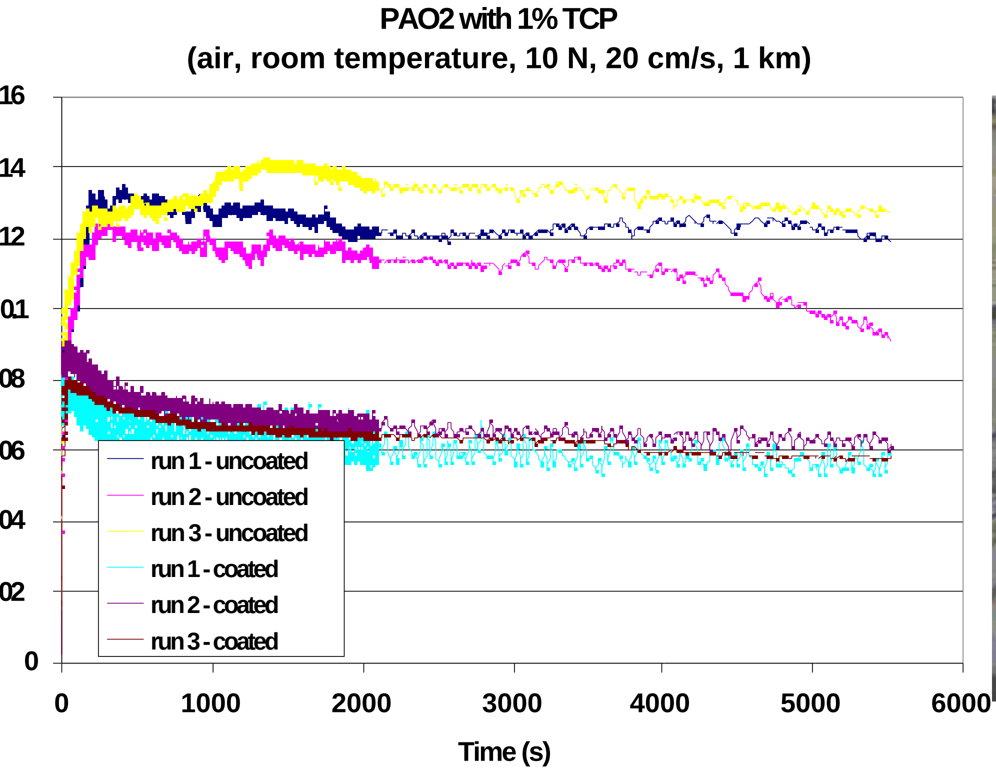
mpact of NFC Coatings on Wear Rate of Steel in Conventional Gasoline



- NFC coating significantly reduced the wear rate of steels

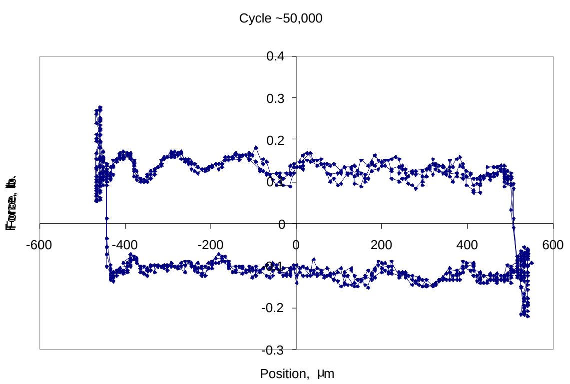
Effect of Lubricant Additives on Tribo-Performance

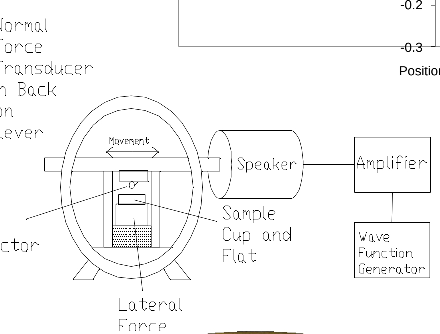


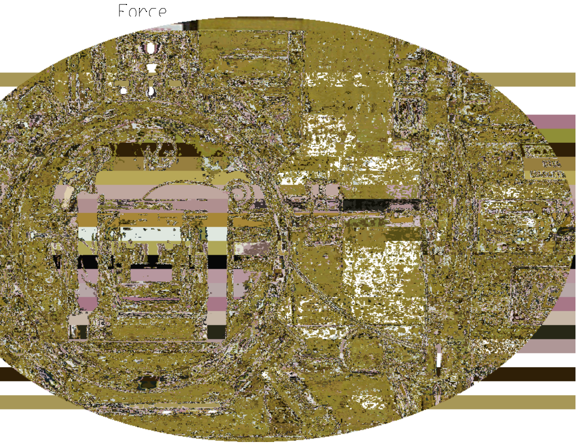
Pin-on-Disc evaluation of synthetic lubricants

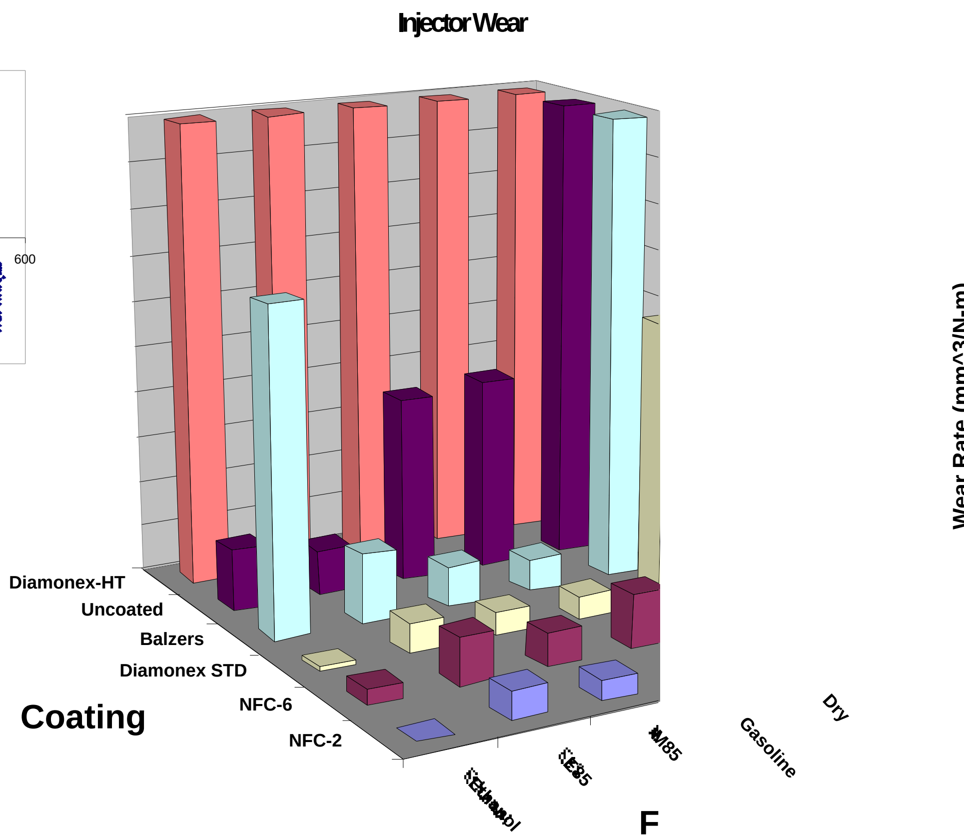
- Use of advanced materials and coatings may necessitate new additive formulations

Low-Amplitude Reciprocating Behavior in SIDI Fuels









- Issue - performance of SIDI components at highe pressures with low-lubricity fuels

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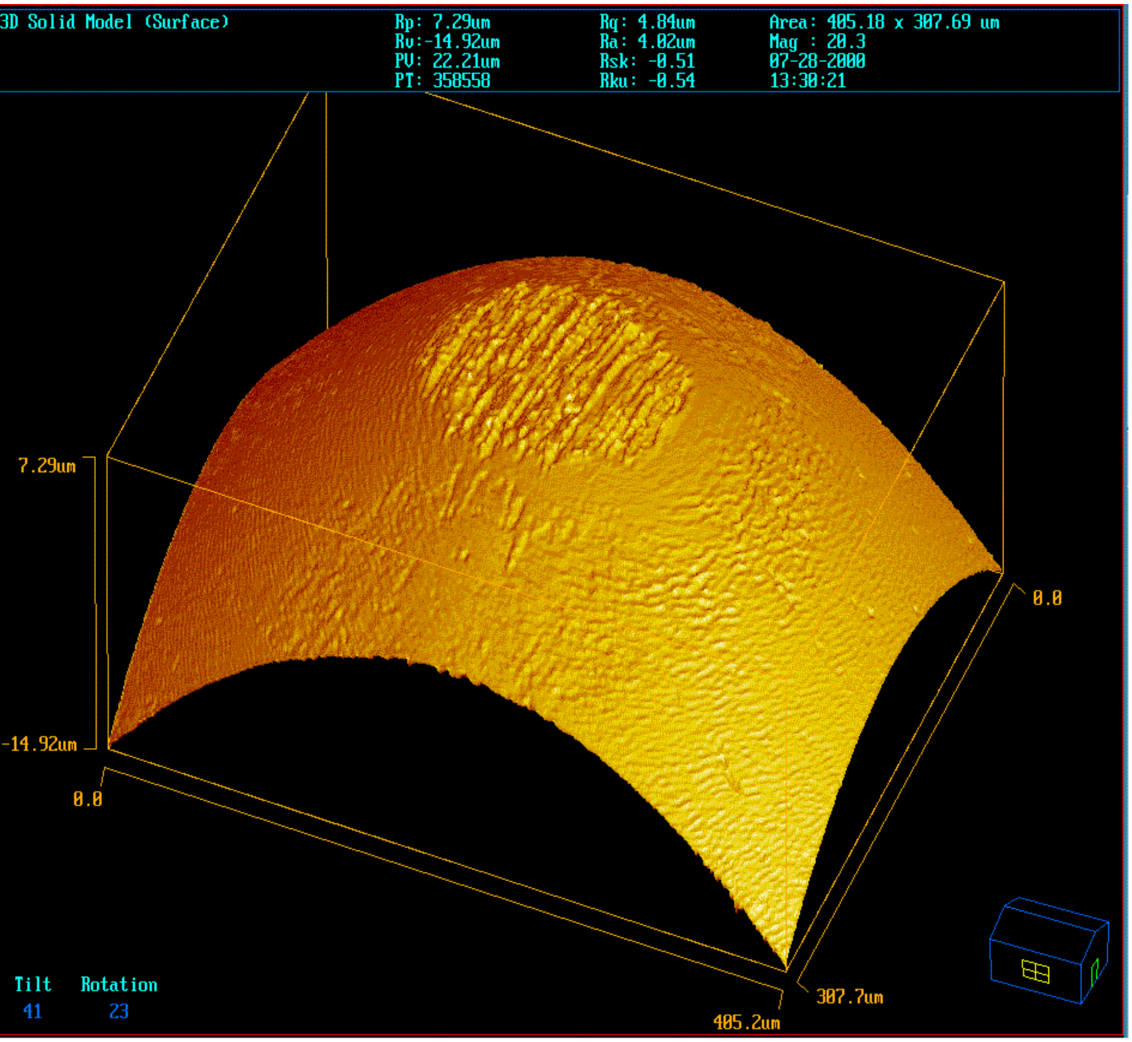
Post-Test Characterization of Wear Rate



- Wear rates determined from high-resolution non-contact profilometry of worn tips

Future Plans

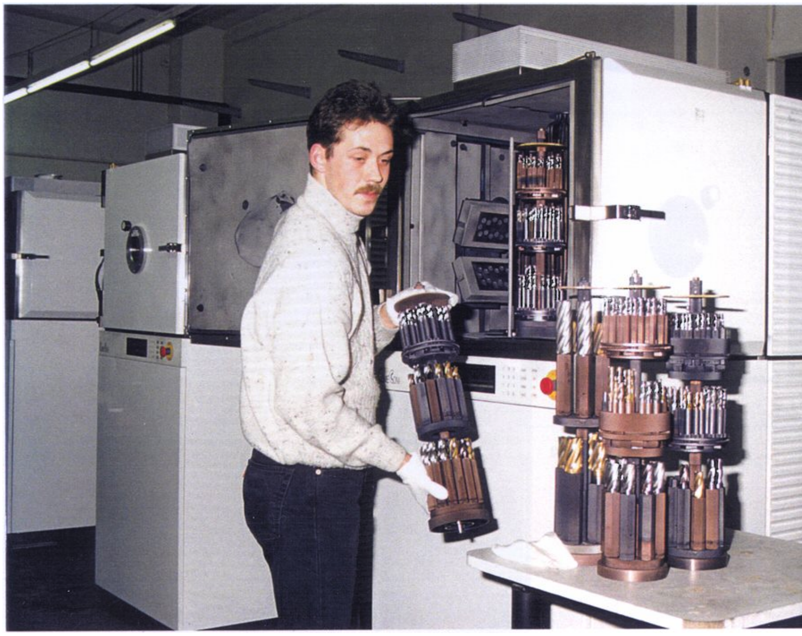
Characterization of NFC tribological performance in fuels and lubricants

- Fuels - use DECSE fuels and determine wear and scuffing parameters, effect of long-term exposure to fuels
- Lubricants - effect of additive packages on wear and scuffing performance, low-emission lubricants, study effect of EGR on lubricant performance material/coating durability/reliability

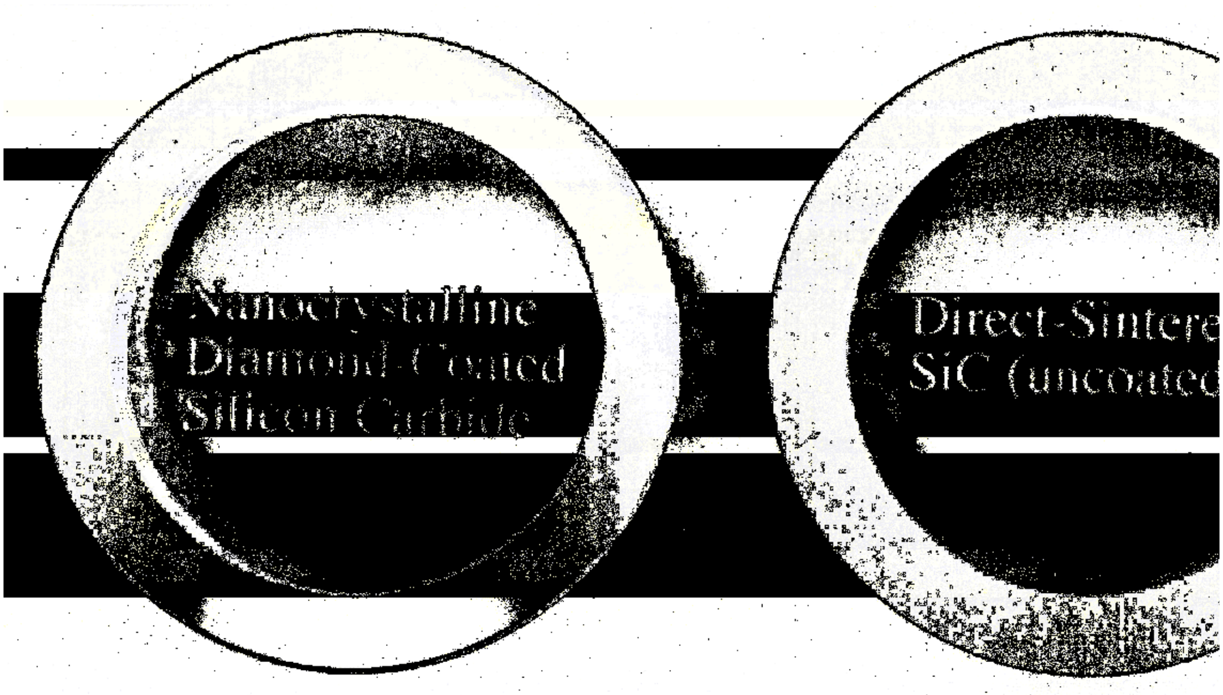
Continue to coat prototype components for fuel component rig and engine tests

Address scale-up and cost issues

- Install commercial scale PACVD unit and modify for NFC process - several approaches are being pursued which involve leveraging State-of-Illinois research funds

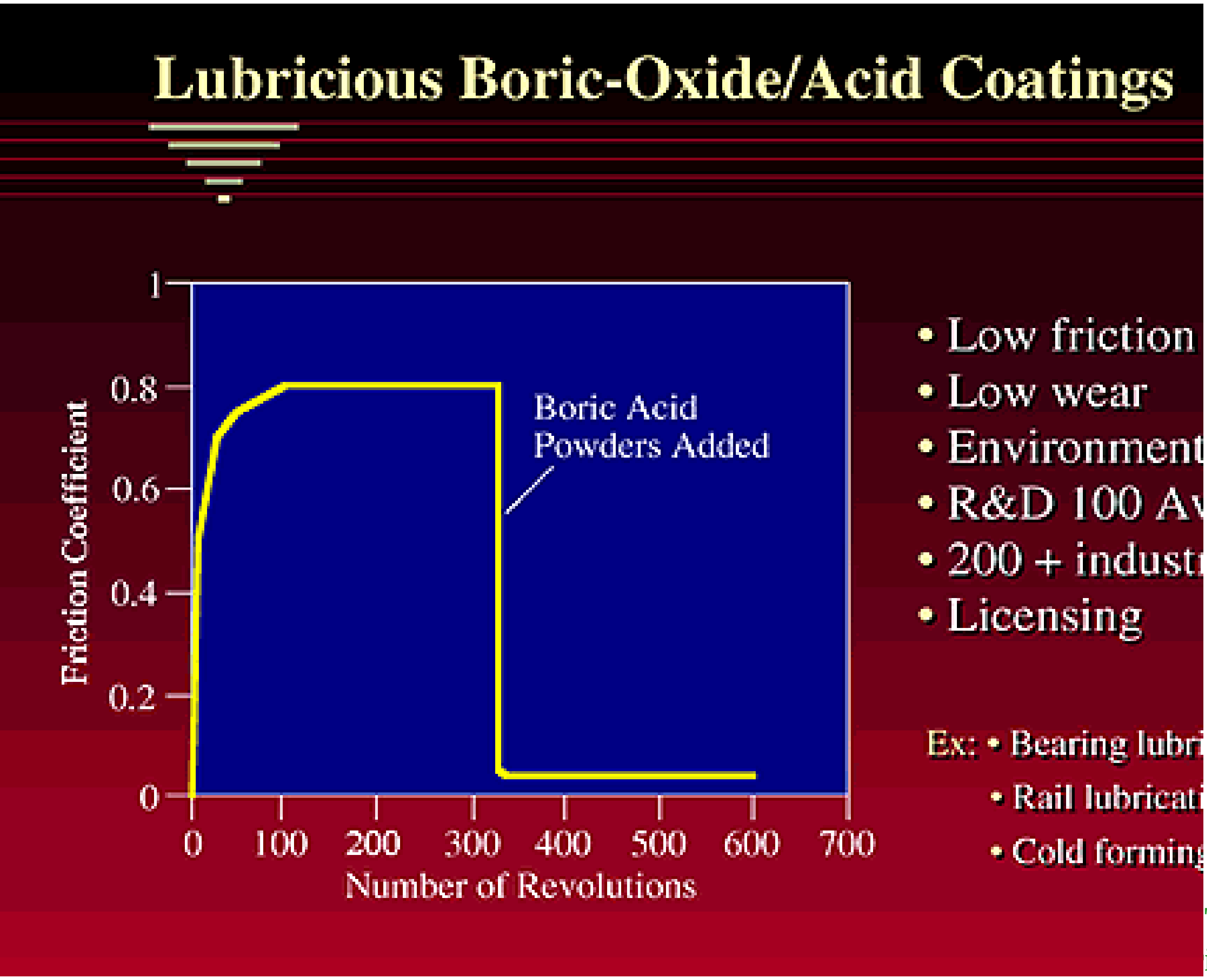


Nanocrystalline Diamond Films
Chemical Process Pumps

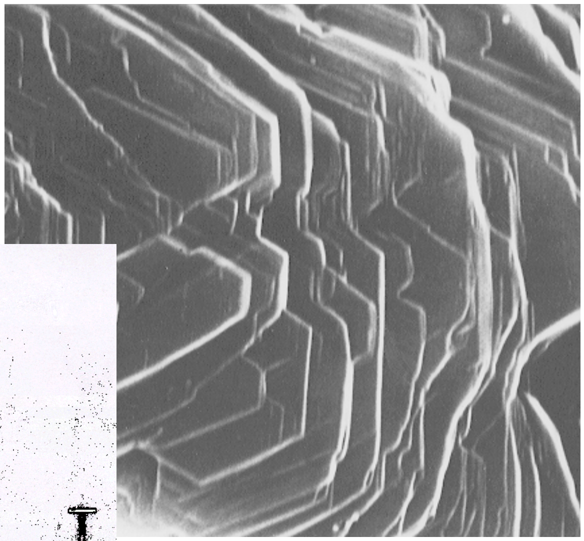


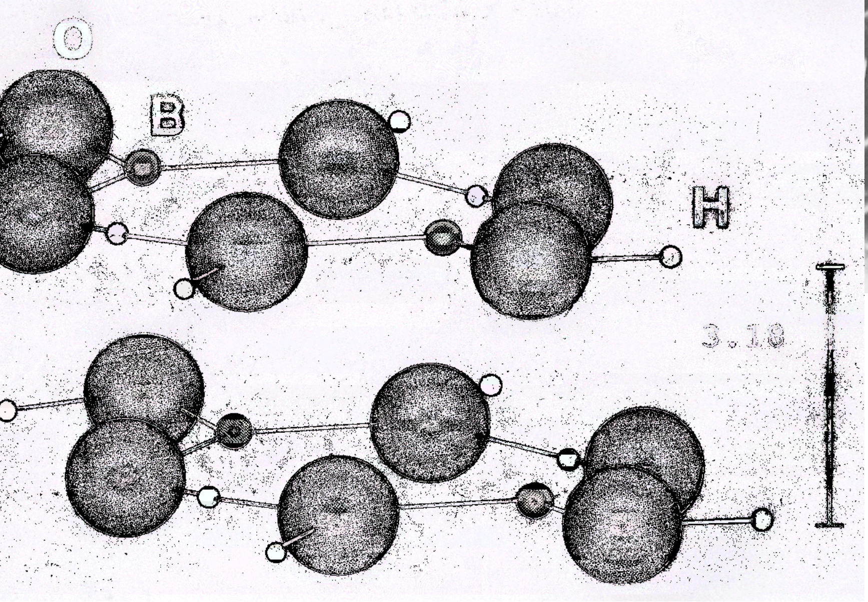
- Fullerene precursor chemistry results in continuous nucleation of diamond crystallites during film deposition

- Reduction of frictional torque by a factor of 6


Lubricious Boric-Oxide/Acid Coatings
Friction Coefficient
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
700
Number of Revolutions
Boric Acid
Powders Added
• Low friction
• Low wear
• Environment
• R&D 100 Av
• 200 + industr
• Licensing
Ex: • Bearing lubri
• Rail lubricati
• Cold forming

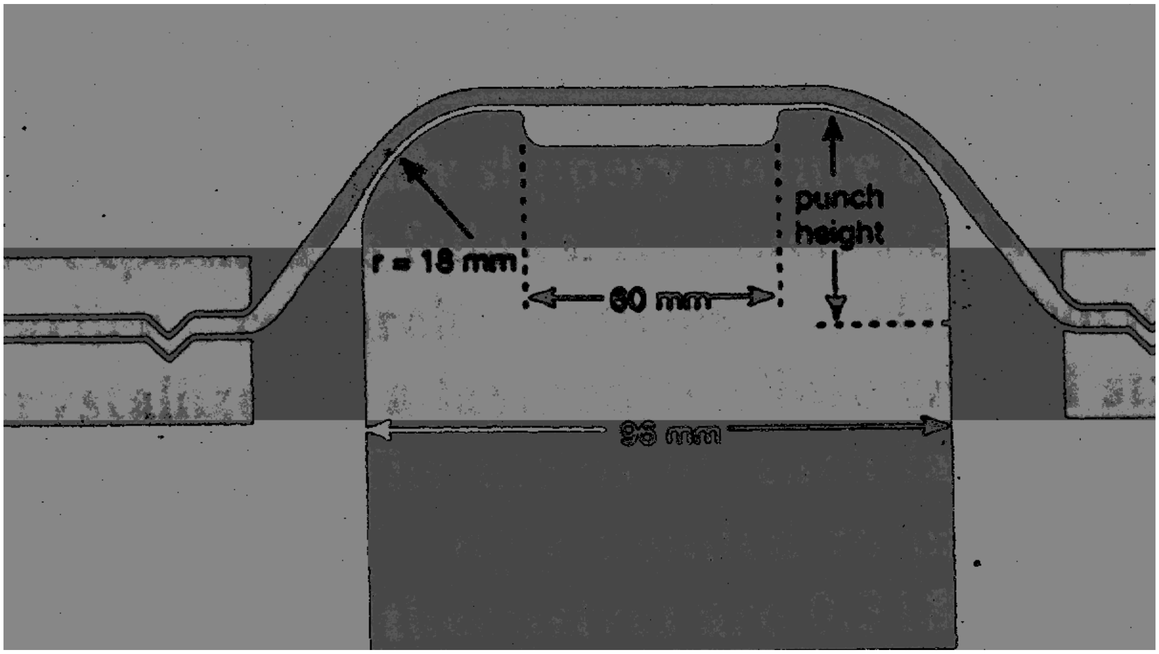
Layered Structure of Boric Acid Provide Low Friction



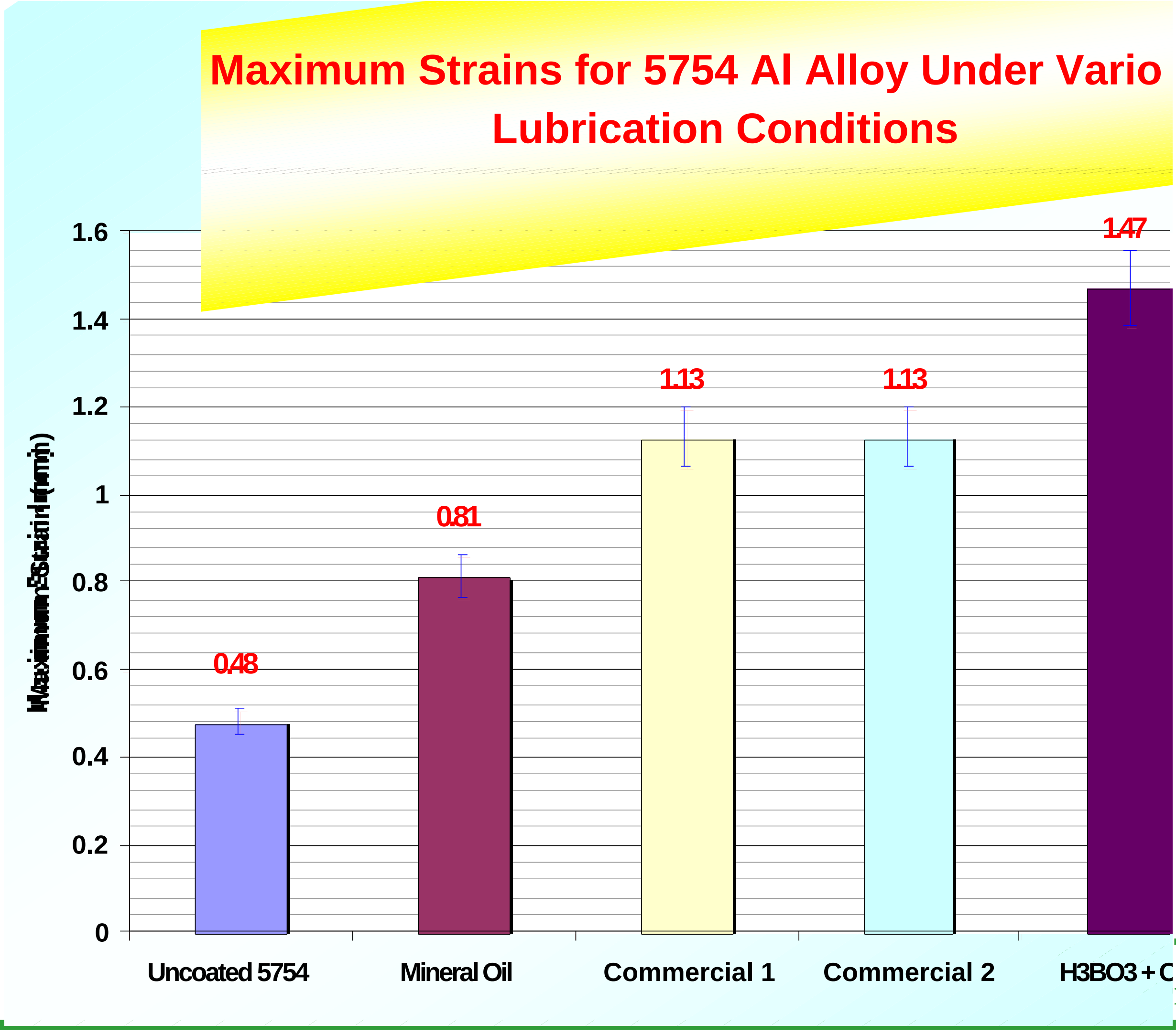


- Layered microstructure of boric acid films provide low shear strength and high compressive strength

Metal-Formability Test Configuration



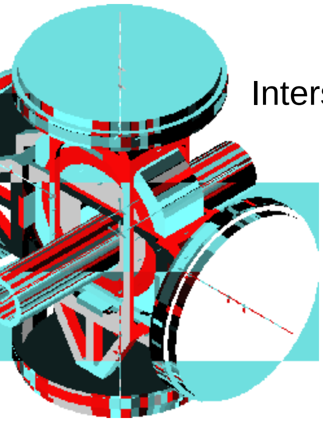
Formability of 5754 Aluminum



Technology Divisio
ibology Section

Critical Tribological Components
- Fuel Cell Compressor/Expanders

Concept	Component	Tribo E
Variable Displacement	-Piston Seal -Bearing Pad	Dry/Saturate greased; Slic moderate loa Polymers, Ca
Scroll	-Tip Seal (Scroll) -'Wall' Seal (Scroll) -Flat-Plate Thrust Washer (Drive Assembly) -DrivePlate Rollers (Drive Assembly) +Proprietary Component	Dry/Saturate Sliding and F moderate to Aluminum, P Steels
Turbine	-Radial Journal Bearing -Thrust Washer	Dry/Saturate 100k rpm; St
Intersecting Vane	-Vanes -Seals -Bearings	Dry/Saturate Sliding; < 10 loads; Alumi materials



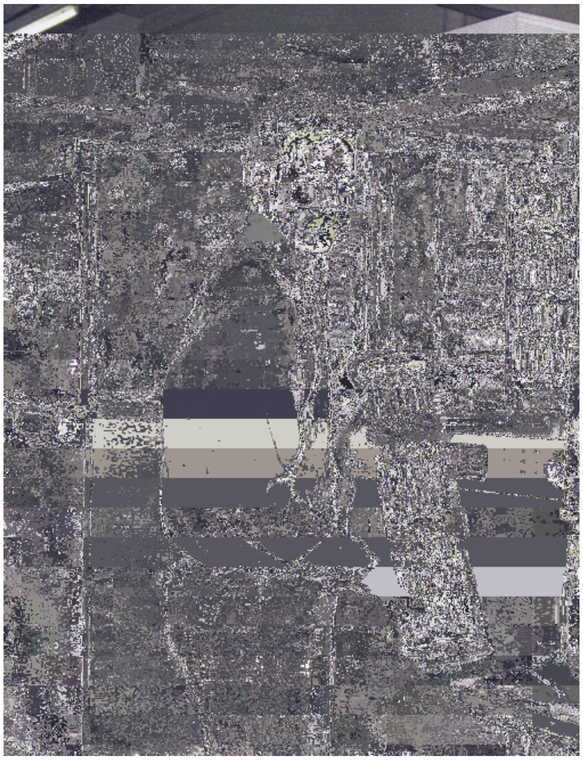
Tech Transfer of NFC Process

Over 3500 Inquiries from industry; 80 NDAs established; 30 WFOs.

Field tests of NFC coatings are coming back positive.

Companies want to know where they can have NFC films deposited commercially

Argonne working with CemeCon to develop a commercial NFC coating system using Argonne's plasma-enhanced chemical vapor deposition technology



Gas Turbine Coatings

Develop New Seals for Regenerative Heat Exchangers for Gas Turbine Hybrid Vehicles (PNGV)

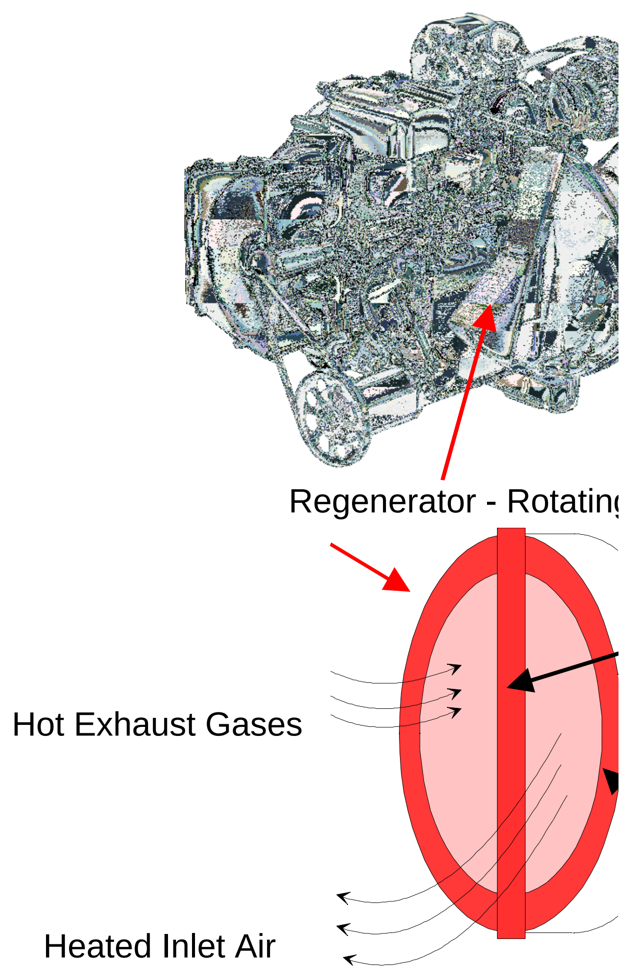
- Heat Exchanger Crucial for Obtaining High Thermal Efficiency
- Core Seals Critical to Operation of Regenerative Heat Exchangers

Regenerator Core Seals

- Hot Cross-Arm Seal
- State-of-Art: 800 C, Plasma-Spray
- Needs: > 1000 C, Lower Cost
- Peripheral Rim Seals
- State-of-Art: 400 C, Stabilized Graphite
- Needs: > 600C, Lower Cost

Research Addresses Durability, Chemical Compatibility, and Manufacturability of Seals

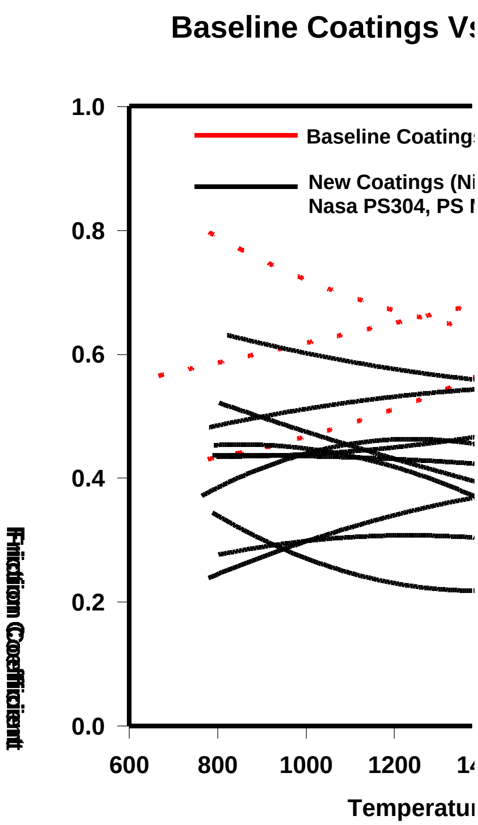
- New Seal Compositions
- Low-Cost Seal Fabrication Processes



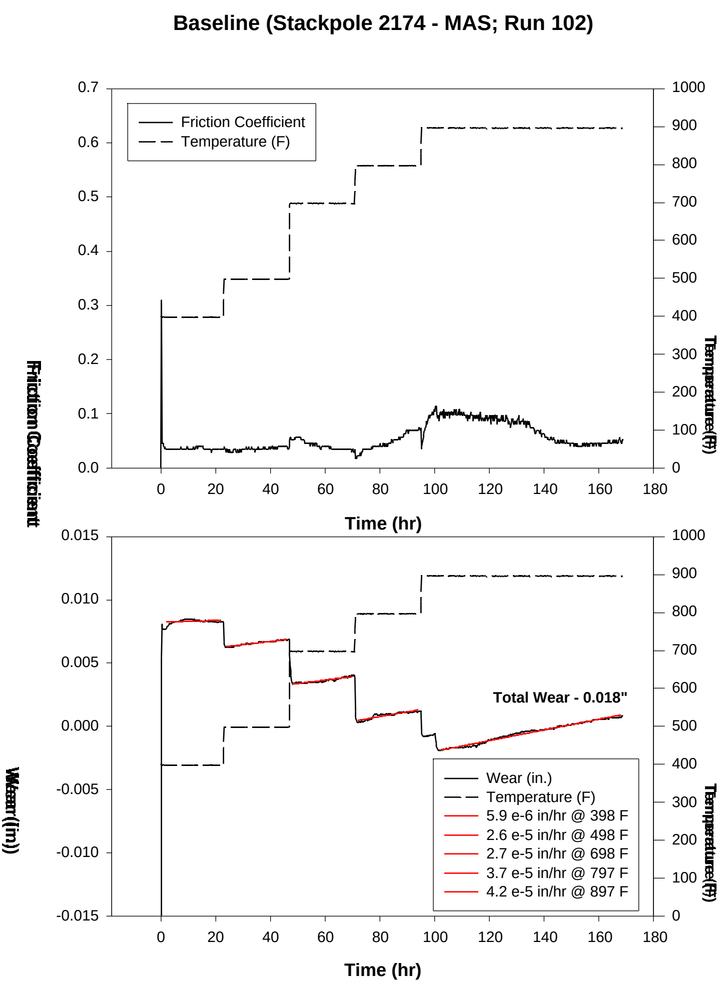
Hot Cross Arm Coatings

Results

- Several new compositions have been identified that meet or exceed baseline coatings in terms of friction and wear
  - NiO/BaOTiO2, MgO/CaF2, NASA PS 300 series, Tribolite PTA
- New coatings are stable at elevated temperatures necessary to achieve desired gas turbine fuel efficiencies
- New processes identified to reduce seal manufacturing costs
  - Plasma-Spray
  - Powder Metallurgy
  - Casting



Carbon Seal Development



- **Evaluating Friction and Wear Behavior of Carbon Based Materials to Replace Baseline Stabilized Graphite**
  - Low-Cost Process to Replace Current Machining Process (Pieces machined from large billets)
  - Current Material No Longer Available
- **Results:**
  - Approximately 50 different Types of Carbon Based Materials Screened
    - Graphite's
    - Carbon/Carbon Composites
    - High-Temperature Polymers
    - Graphite/Resin Composites

Research Needs/Opportunities

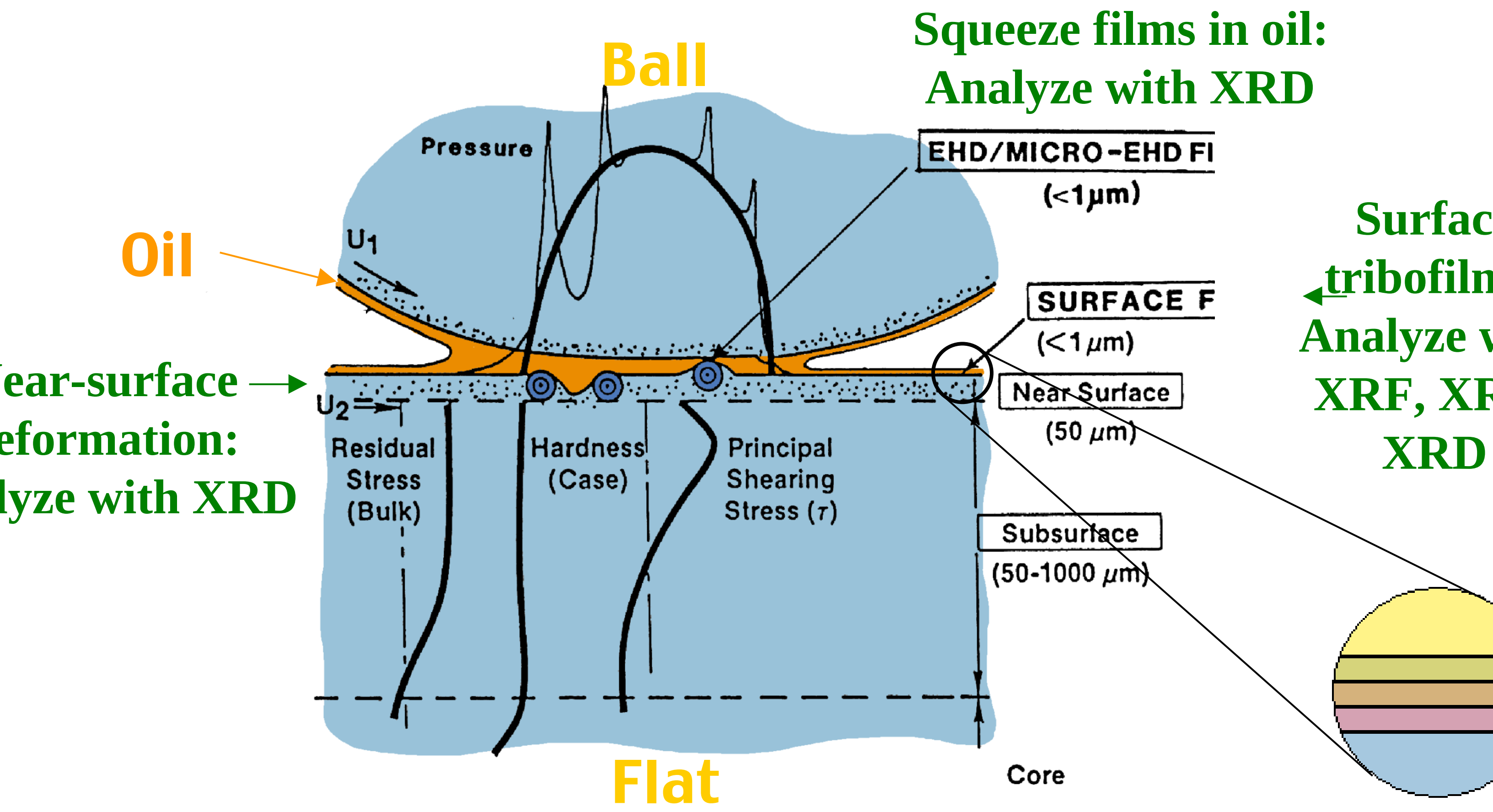
- **Tribology Section receives Programmatic Funding - Not Block Funding**
  - R&D structured to meet sponsors needs
- **Tribology Sponsored R&D**
  - Transportation
    - Coatings
    - Fuels & Lubricants
    - Basic - boundary layer lubrication - APS
  - Nanotribology
  - Biomedical
- **New Opportunities/Needs**
  - Cold Climate Tribology
  - Plasma Modeling

Achieving Emission, Efficiency, & Reliability/Durability Goals is Critically Dependent on Friction and Wear

Component	Issue	Emission	Efficiency	Reliability/Durability
ngine – Fuel System				
Fuel injector	(a)	X	X	X
Fuel pump			X	X
ngine – Bearings				
Main	(b)	X	X	X (EGR)
Crankshaft Rod		X	X	X (EGR)
Crankshaft Wrist Pin		X	X	X (EGR)
ngine – Valve Train				
Cam	(c)		X	
Rocker arm				
Stem/guide			X	
ngine – Cylinder				
Piston skirt	(d)	X	X	
Piston rings		X	X	
ngine – Air supply				
Turbocharger	(e)		X	X
owertrain				
Transmission	(f)	X	X	X
Axle			X	X
Final drive			X	X
uxiliary Load				
Water/coolant pump	(g)		X	X
Oil pump			X	X
Fan			X	
Air & Heating			X	X
ftertreatment				
NOx catalysts	(h)	X		
PM traps		X		
uel Cells- Compressor / Expander				
Bearings, seals, etc.	(i)		X	X

- (a) low-lubricity (e.g. low-S, DME, alcohol-based) fuels, higher injection pressures / tig gaps, corrosion
- (b) low emission lubes & additives, EGR (s combustion products – oil degradation), hig power density, extended drain intervals, wea resistance & low-friction
- (c) EGR (soot, combustion products – oil degradation), lightweight materials – wear resistance, scuffing, seat wear
- (d) EGR (soot – abrasion), corrosion, thermal–efficiency - leakage
- (e) erosion, seal leakage – oil consumption
- (f) power density / wear & efficiency, fill-fo life lubes & fluids, contact fatigue & wear, 1 million-mile warranty
- (g) water and oil coolant degradation – corrosive & abrasive wear, effect of nanoflu on tribo-properties
- (h) impact of low-S fuels, and low-S, P, etc. lubes required for aftertreatment on engine components
- (i) non-lubricated seals, lightweight materia high power densities

Using the APS to Analyze Boundary Lubrication



APS - BLL
Surface Tribofilms

What is Known

ds to dissociate when
sure removed.

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artly crystalline.

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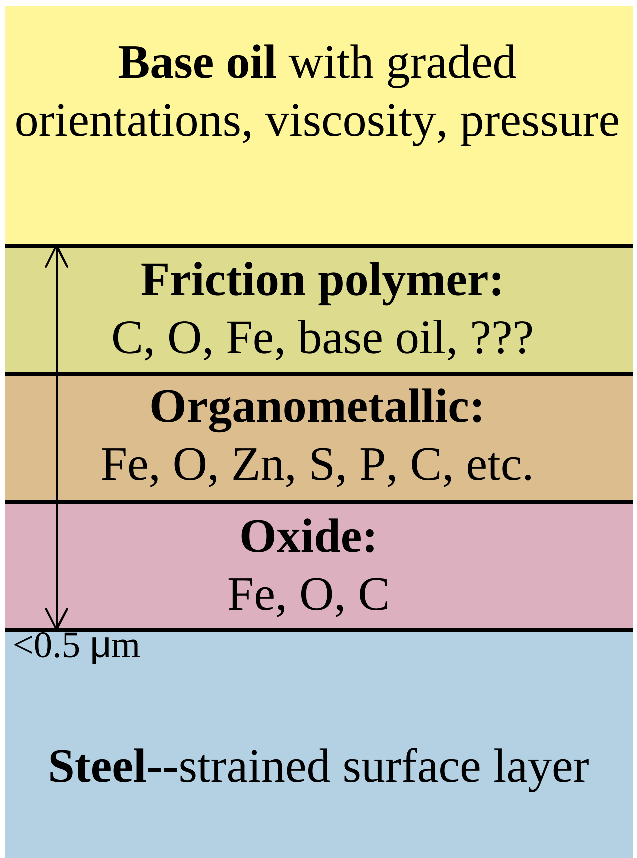
vear

omposition from post-
eaning analysis: TEM,
PS, etc.--modified!



APS Technique

During interrupted or "dynamic" wear test:

•XRF: composition of e
layer

•XRR: thickness and density of each layer

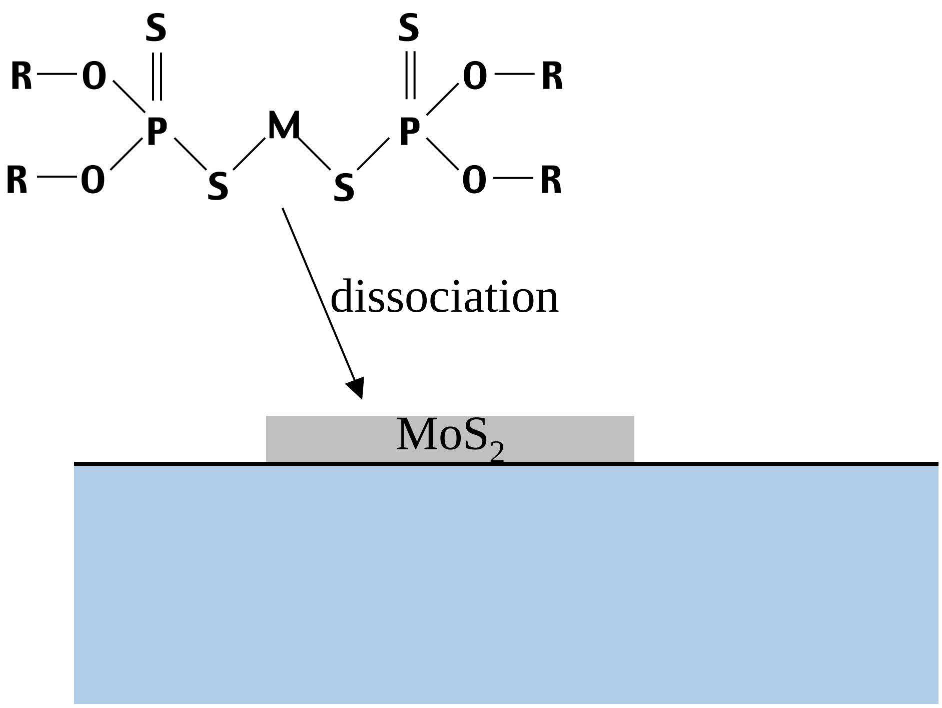
•XRD: crystalline conte
in each layer

During wear test:

•XRD: strain as a functi
of depth in steel

APS - BLL
Oil Additives at Surfaces

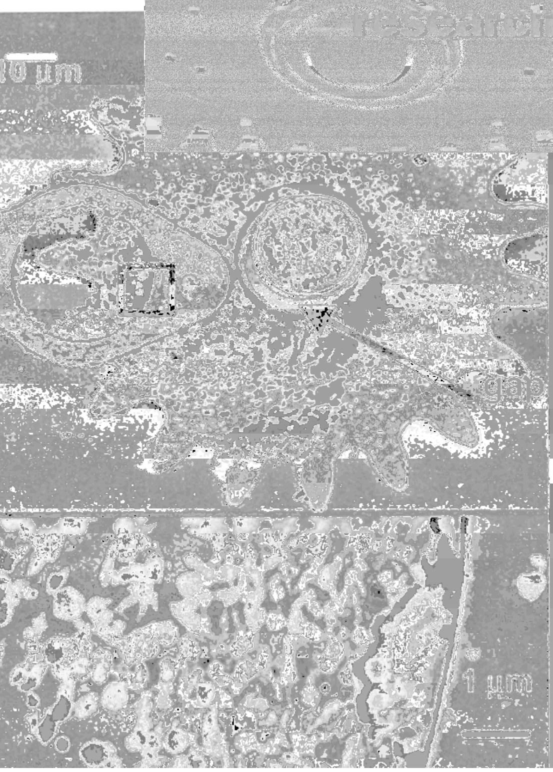
etal dialkyldithiophosphate (MDDP) additives
(M = Zinc, Mo, etc. R=organic)



Additive chemicals, such a
MDDP shown here, reduce
friction, wear, corrosion,
and oxidation. They are
thought to dissociate and
form solids on the surface,
such as MoS_2. The details
are not well understood. A
APS, XRF can find the
elements and XRD can
identify the crystalline
solids.

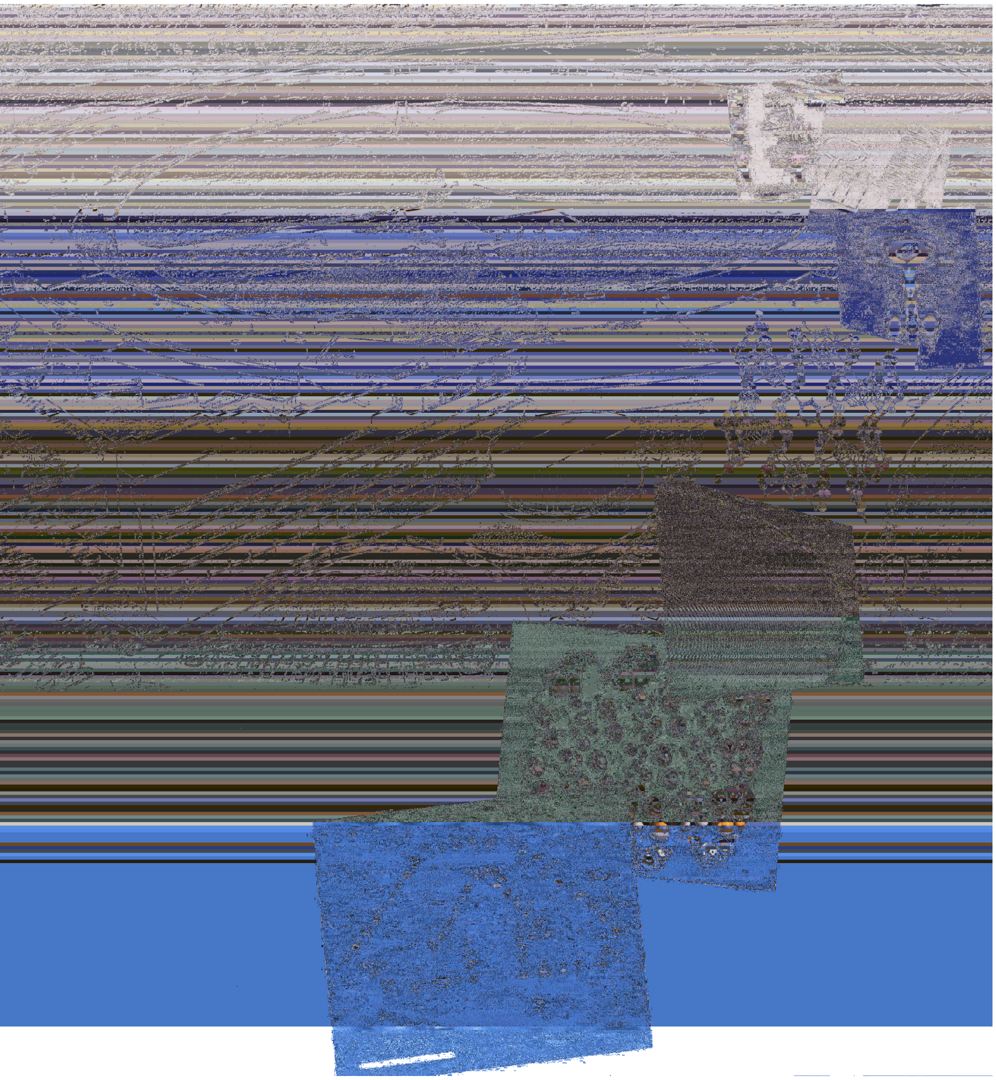
Impact of Tribology on MEMs

(Science News, vol 158, 56-59)



- Friction and wear of MEMs devices may limit their performance and require use of solid lubricants

Argonne's NanoScale Materials Proposal



- A key element in DOE's NanoTechnology Initiative
  - Closely tied to APS
  - Nanofabrication
  - Nanocharacterization
  - Computation

Cold-Climate Tribology

- Engine lubricants and fuels are extremely viscous at low temperatures
  - block heaters
  - run vehicles continuously
  - multi-grade lubricants
  - lower viscosity lubricants - what do you do when vehicles warm up - application of wear-resistant coatings for boundary lubrication

Summary

- Solid lubrication/coatings can be very effective in protecting critical surfaces during boundary lubrication
- Key barriers exist
  - technical -
  - politics - within funding agencies and within industry
  - critical to develop teams - industry, national labs, academia